# Associated J/ψ production in heavy-ion collisions at the LHC

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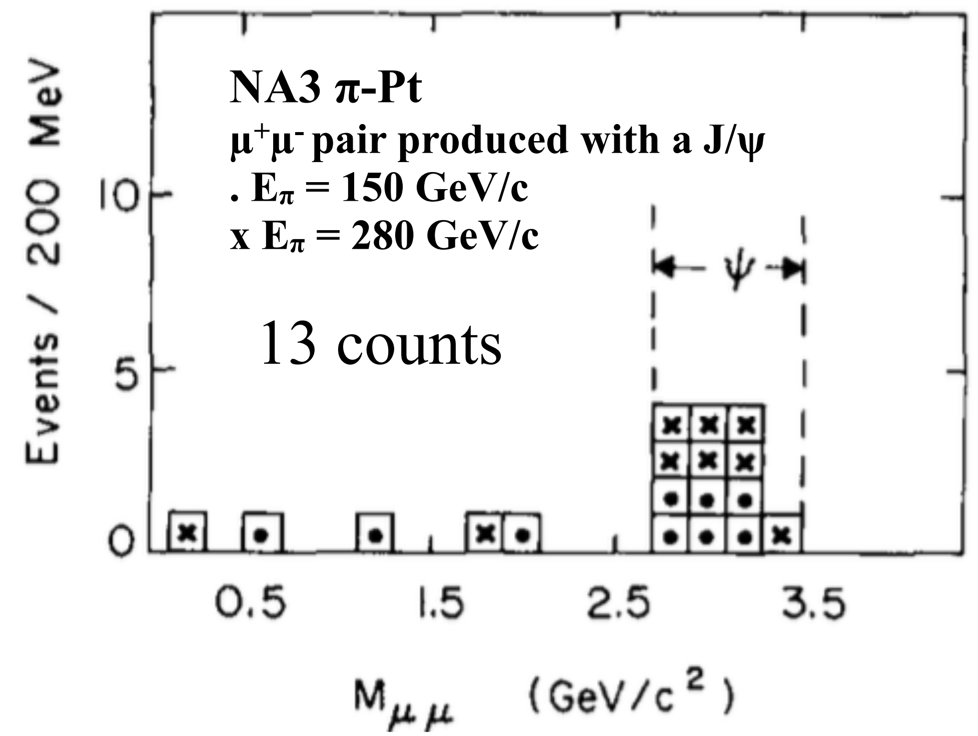
- Associated J/ψ production in p-p and heavy-ion collisions
- Nuclear modification factor in heavy-ion collisions
- Expected rates for associated J/ψ production at forward-y in Run 2 at the LHC in ALICE and LHCb
    - J/ψ + J/ψ
    - J/ψ + μ ($p_{T,\mu} > 4$ GeV/c) as a probe of J/ψ + open heavy flavour in ALICE
    - J/ψ + D in LHCb

# Associated J/ψ production

Double J/ψ production observed first at CERN/SPS by NA3 collaboration in π-Pt and p-Pt PLB 114 (1982) 457, PLB 158 (1985) 85




Several studies in p-p collisions at Tevatron and LHC:

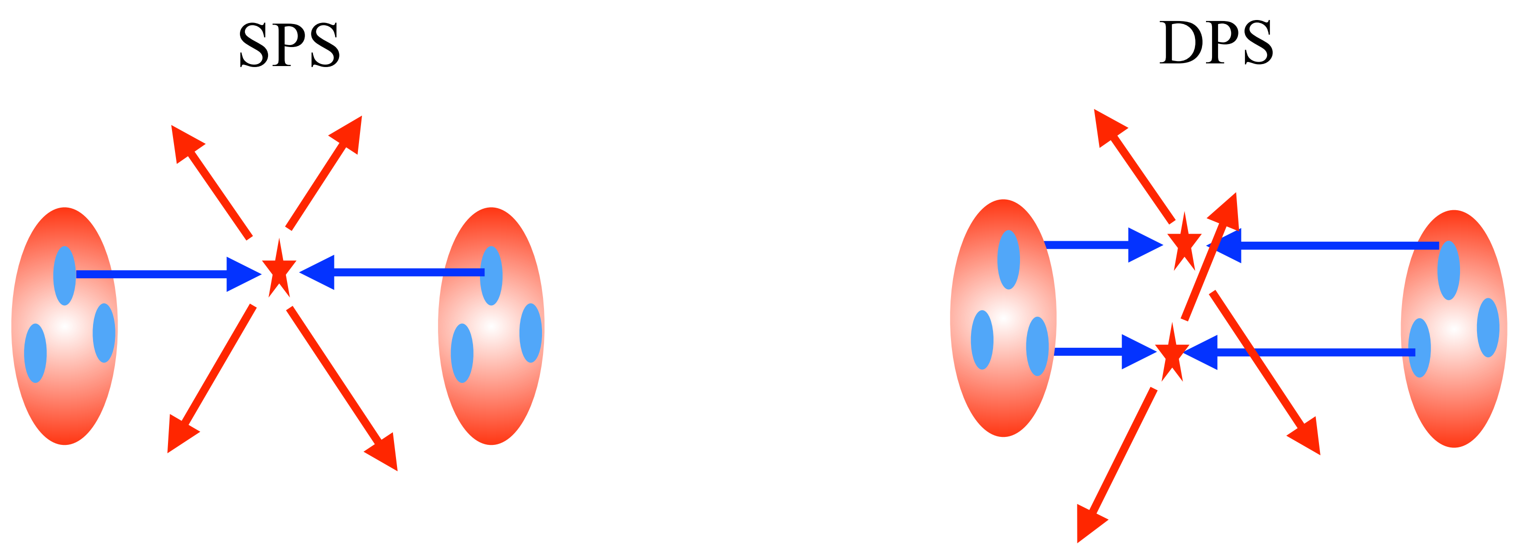
- D0: J/ψ pair PRD90 (2014) 11,111101, J/ψ+ϒ arXiv:1511.02428
- ATLAS: J/ψ+W JHEP1404 (2014) 172, prompt and non-prompt J/ψ+Z EPJC75 (2015) 5,229
- CMS: J/ψ pair JHEP09 (2014) 094
- LHCb: J/ψ pair PLB707(2012)52, J/ψ + open charm JHEP06 (2012) 141

Provide inputs for:

- quarkonium production mechanisms in p-p collisions: interplay between perturbative and non-perturbative domains
- double parton scattering (DPS) mechanisms: correlation between pairs of partons in the proton
- in heavy-ion collisions, double-particle production are expected to be enhanced by nuclear scaling

# Single vs double parton scatterings

At high energy in p-p collisions: probability of multiple parton scattering is expected to increase




DPS:
- two parton interactions from a single hadron-hadron collision
- simple assumption: the two parton interactions are independent

$$\sigma^{P_1+P_2} = \frac{m}{2\sigma_{\mathrm{eff}}}\sigma^{P_1}\sigma^{P_2}$$

with m = 1/2, 1, 2 symmetry factor depending on the process

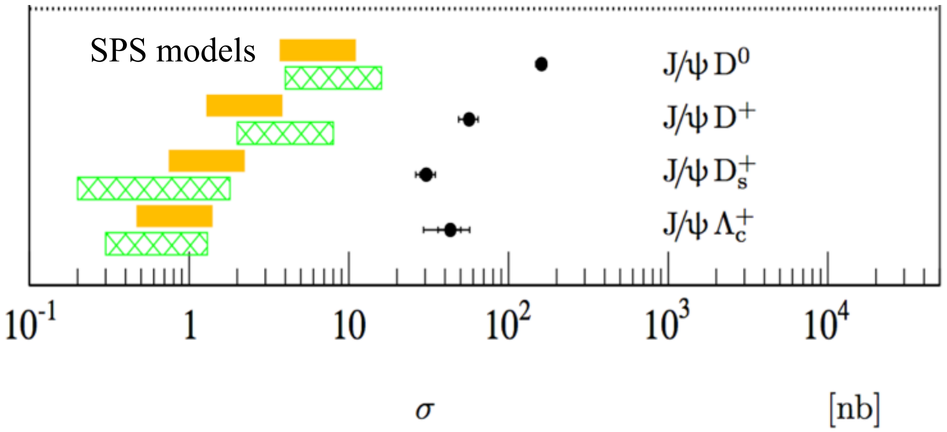
$\sigma_{eff}$ :
- parametrizes the effective spatial area of the parton-parton interactions
- expected to be universal (process and energy-independent)

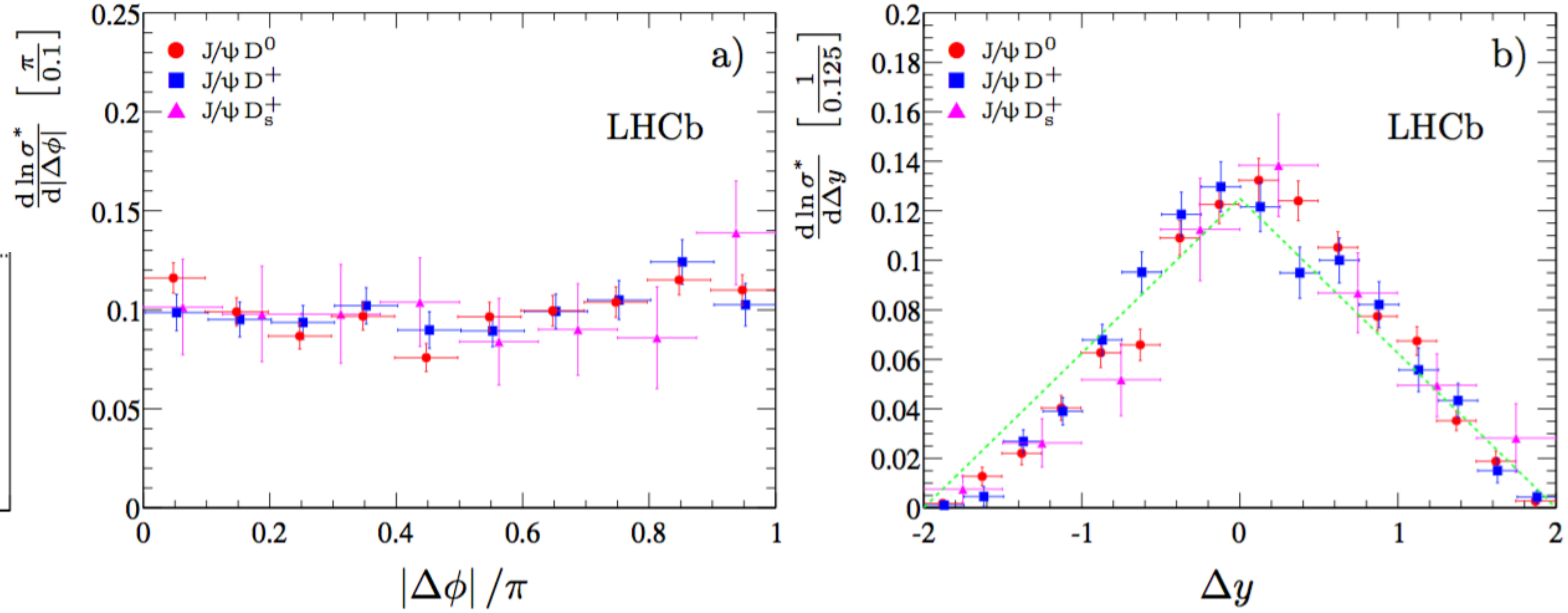
# Single vs double parton scatterings

Disentangling SPS vs DPS via rapidity and angular dependence

## J/ψ + open charm in LHCb

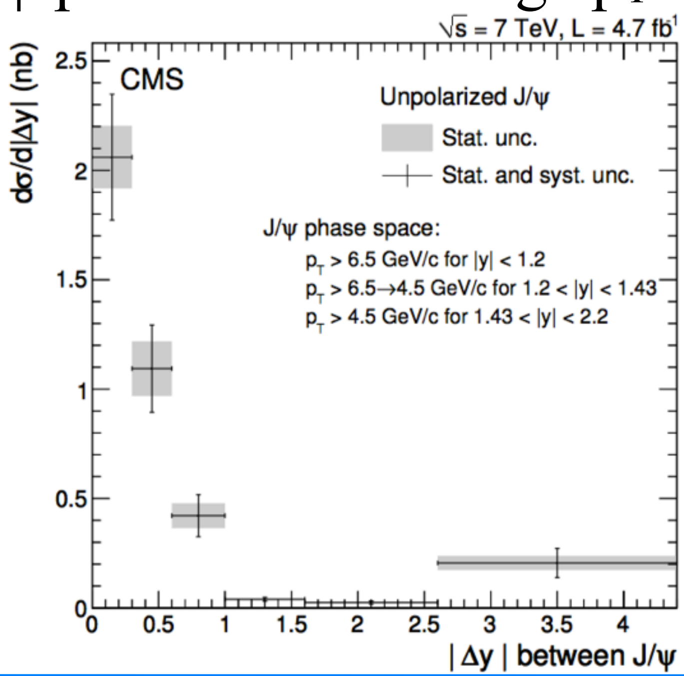
JHEP06 (2012) 141 (7TeV)



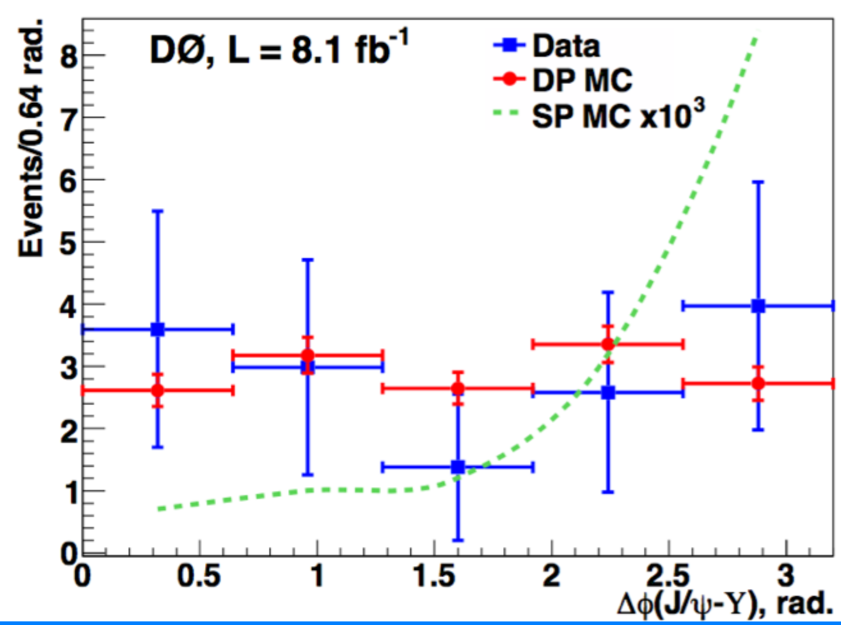

→ cross-sections 10 times larger than SPS models and DPS supported by rapidity and angular dependence

## J/ψ pair in CMS at large $p_T$ JHEP09 (2014) 094




→ contribution at large Δy expected from DPS only

## J/ψ + ϒ with D0 arXiv:1511.02428



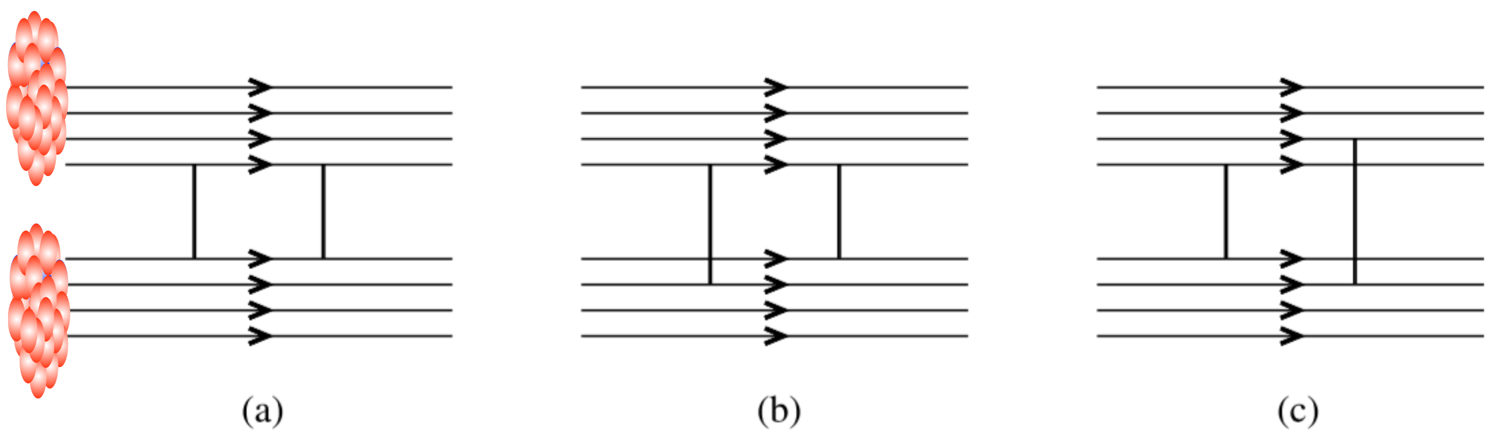

→ DPS contribution supported by angular dependence

# Heavy-ion collisions

Nuclear modification factor: $$\mathrm{R_{AA}} = \frac{1}{\mathrm{A}^2} \frac{d\sigma^{\mathrm{AA}}/dp_T dy}{d\sigma^{pp}/dp_T dy}$$

If no nuclear effect, $\mathrm{R_{AA}} = 1$ and scalings of cross-sections in A-A wrt p-p collisions are:

- SPS scaling = $\mathrm{A}^2$
- DPS scaling in A-A collisions d'Enterria and Snigirev, PLB 727 (2013) 157




(a) colliding partons belong to the same pair of nucleons
(b) two partons of one nucleon collide with two partons from different nucleons
(c) colliding partons belong to different nucleons

→ **relative contributions are 1:4:200 in Pb-Pb**

Geometric factor in heavy-ion collisions: enhancement of DPS in A-A wrt p-p by $\mathrm{A}^{3.3}/5$. For Pb nuclei, enhancement by 9e6.

In p-Pb, enhancement of DPS in p-A wrt p-p by $\mathrm{A}^{1.5}/\sqrt{10}$ (Strikman and Treleani PRL88(2002)031801). For Pb nucleus enhancement by ~950 (~600 in: d'Enterria and Snigirev, PLB 718 (2013) 1395).

While DPS may not dominate over SPS in p-p collisions, DPS is enhanced in p-A and A-A!

# Nuclear modification factor for associated J/ψ production in heavy-ion collisions

Assumptions:
- factorization of nuclear effects
- three different hypotheses on SPS and DPS relative contributions in p-p collisions

One defines:

$$\mathcal{F} = \frac{\mathrm{DPS}}{\mathrm{DPS} + \mathrm{SPS}}$$

$\mathcal{F} = 0$ → only SPS

$\mathcal{F} = 1$ → only DPS

Nuclear modification factor in proton-nucleus:

$$\mathrm{R}_{\mathrm{pA}}^{P_1+P_2} = \frac{\sigma_{pA}^{P_1+P_2}}{A\sigma_{pp}^{P_1+P_2}} \longrightarrow \mathrm{R}_{\mathrm{pA}}^{P_1+P_2} = \mathrm{R}_{\mathrm{pA}}^{P_1} \times \mathrm{R}_{\mathrm{pA}}^{P_2} \times \left[(1-\mathcal{F}) + \sqrt{\frac{A}{10}}\mathcal{F}\right]$$

Nuclear modification factor in nucleus-nucleus:

$$\mathrm{R}_{\mathrm{AA}}^{P_1+P_2} = \frac{\sigma_{AA}^{P_1+P_2}}{A^2\sigma_{pp}^{P_1+P_2}} \longrightarrow \mathrm{R}_{\mathrm{AA}}^{P_1+P_2} = \mathrm{R}_{\mathrm{AA}}^{P_1} \times \mathrm{R}_{\mathrm{AA}}^{P_2} \times \left[(1-\mathcal{F}) + \frac{A^{1.3}}{5}\mathcal{F}\right]$$

# Expected rates of associated J/ψ production

Focus on Run 2 and forward rapidities (ALICE and LHCb) at the LHC

Expected delivered luminosity in Run 2 (under discussion):

- p-p collisions at $\sqrt{s}$ = 13 TeV with $\mathscr{L}_{ALICE}$ = 40/pb and $\mathscr{L}_{LHCb}$ = 10/fb
- p-Pb (and Pb-p) collisions at $\sqrt{s_{NN}}$ = 8 TeV with $\mathscr{L}_{ALICE} = \mathscr{L}_{LHCb}$ = 10/nb × 2
- Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5 TeV with $\mathscr{L}_{ALICE}$ = 1/nb

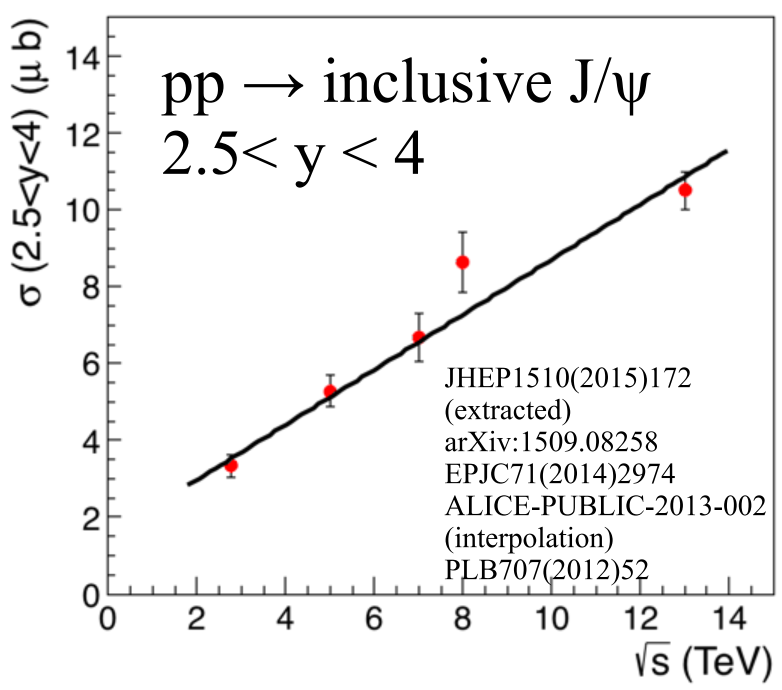
Observables:

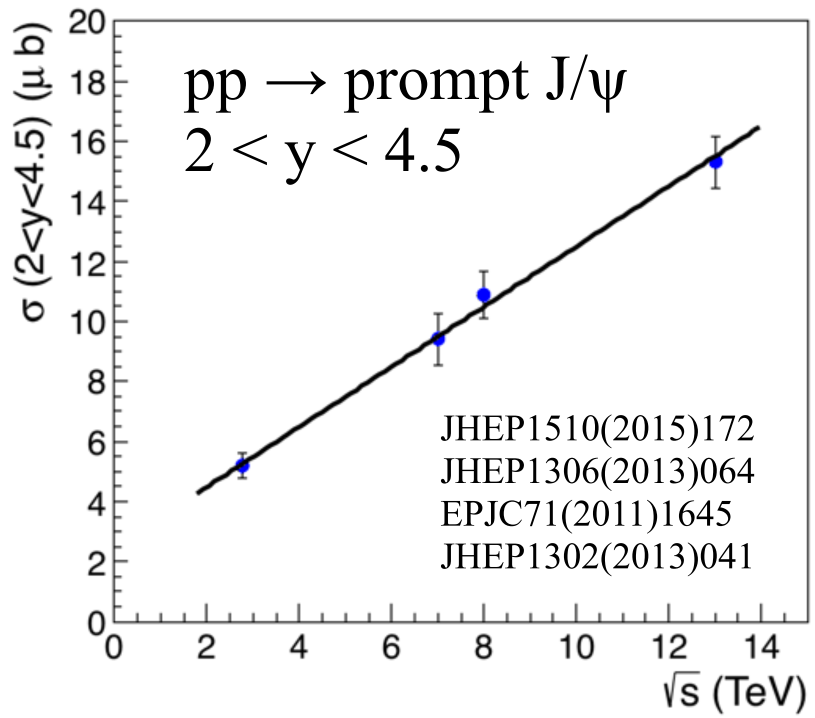
- J/ψ pair production in ALICE (p-p, p-Pb and Pb-Pb) and LHCb (p-p and p-Pb)
- J/ψ+μ ($p_{T,\mu}$ > 4 GeV/c) as a probe of J/ψ + open heavy flavour in ALICE
- J/ψ+D in LHCb

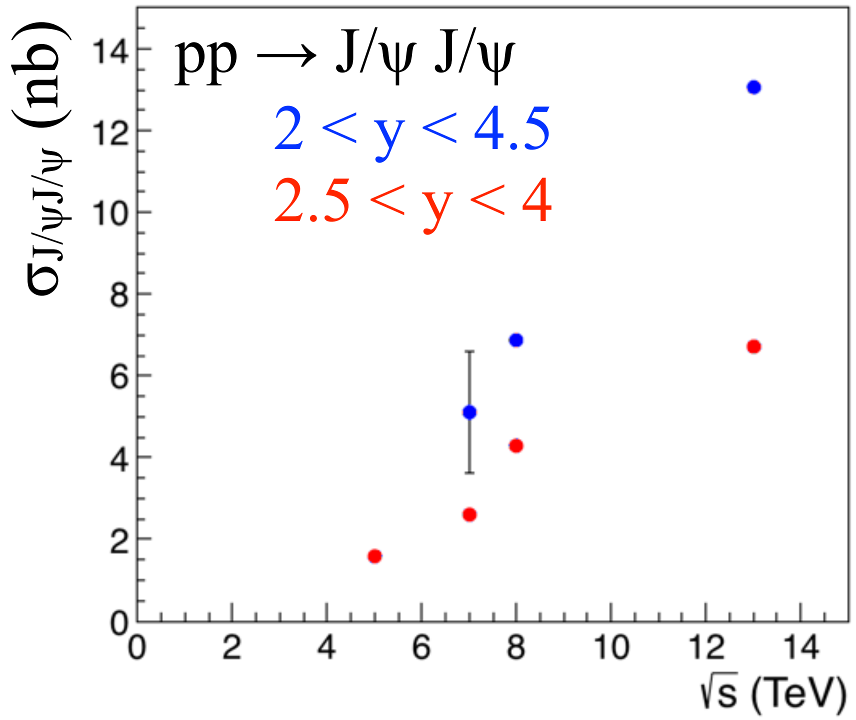
# J/ψ pair production at forward-y vs √s

Inputs:

- J/ψ pair production at 7 TeV in LHCb for $2 < y < 4.5$: $\sigma = 5.1 \pm 0.1 \pm 0.1$ nb PLB707(2012)52
- Assumptions based on the DPS formula:
    1. energy dependence $\propto[\sigma_{J/\psi}(s)]^2$
    2. rapidity dependence $\propto[\sigma_{J/\psi}(y)]^2$
- inclusive J/ψ for $2.5 < y < 4$ (from ALICE+LHCb data)
- prompt J/ψ for $2 < y < 4.5$ (from LHCb data and $\sqrt{s}$ = 5 TeV obtained from a linear fit of existing data)

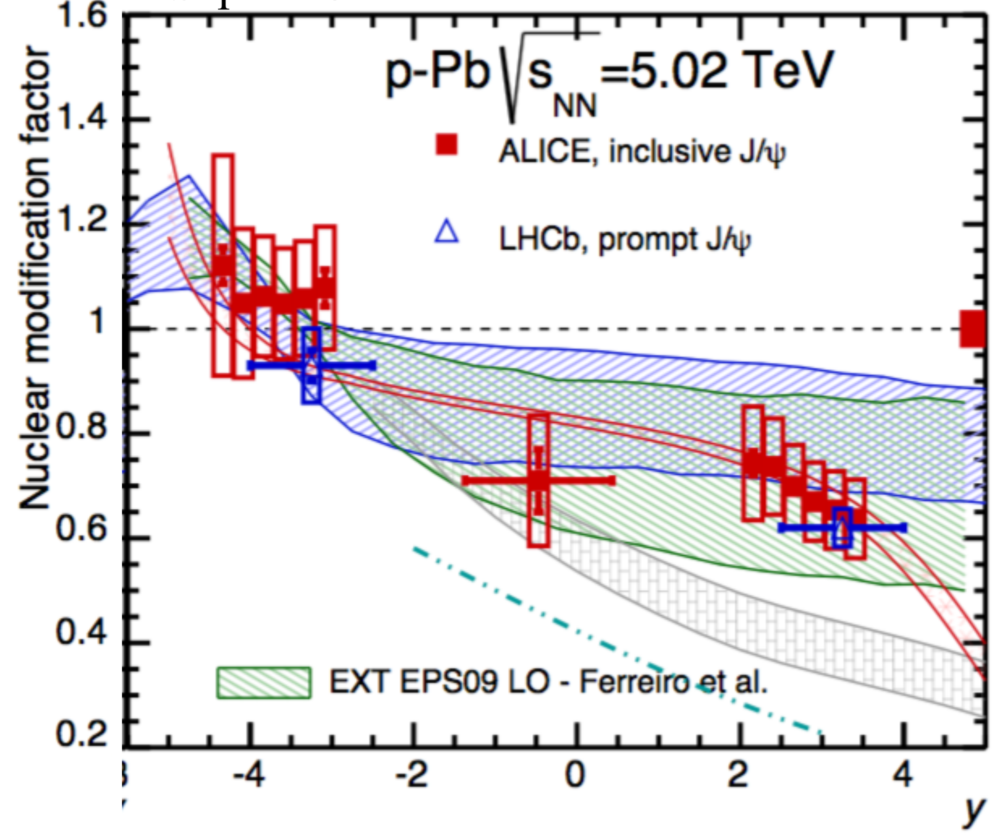


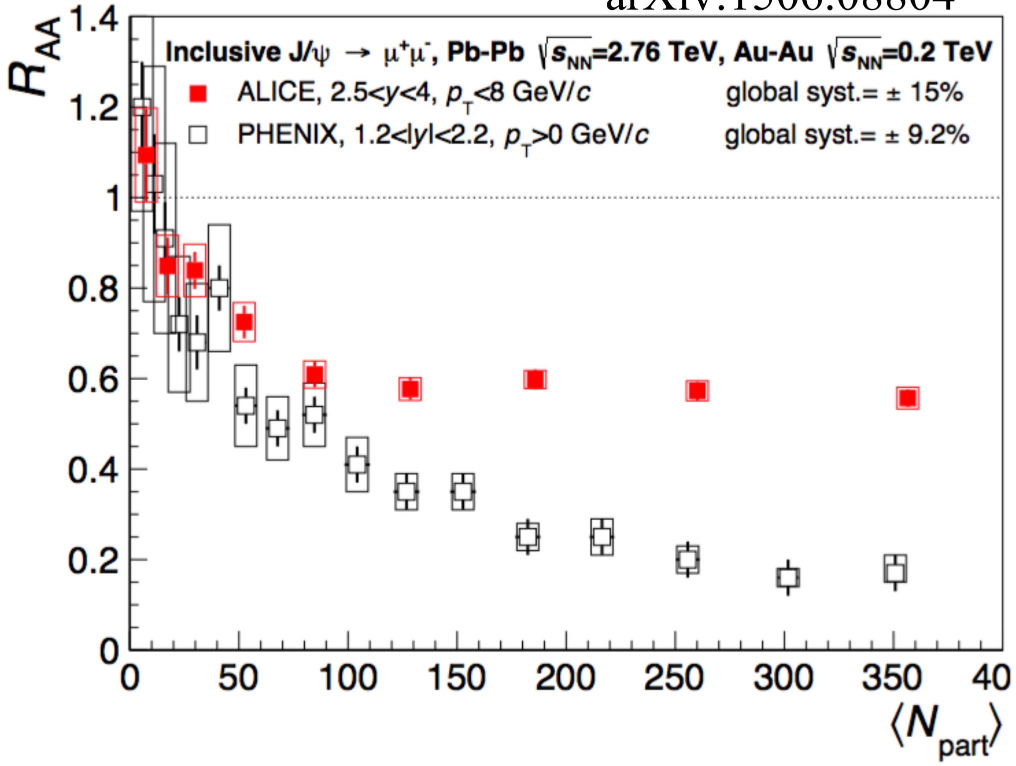



# J/ψ pair production: nuclear modification factor

Sapore Gravis Review arXiv:1506.03981




arXiv:1506.08804




**p-Pb collisions**

$R_{pPb}$(J/ψ) ~ 0.7 at $y_{cms}$ > 0

$$R_{pA}^{P_1+P_2} = R_{pA}^{P_1} \times R_{pA}^{P_2} \times \left[(1-\mathcal{F}) + \sqrt{\frac{A}{10}}\mathcal{F}\right]$$

$\mathcal{F} = 0, 1/2, 1$ → $R_{pPb}$(J/ψ+J/ψ) = 0.5, 1, 2

**Pb-Pb collisions**

$R_{PbPb}$(J/ψ) ~ 0.6

$$R_{AA}^{P_1+P_2} = R_{AA}^{P_1} \times R_{AA}^{P_2} \times \left[(1-\mathcal{F}) + \frac{A^{1.3}}{5}\mathcal{F}\right]$$

$\mathcal{F} = 0, 1/2, 1$ → $R_{PbPb}$(J/ψ+J/ψ) = 0.3, 40, 75

→ (very?) large increase of nuclear modification factor in p-Pb and Pb-Pb depending on DPS relative contribution

# J/ψ pair production rates at forward-y

$$N_{J/\psi J/\psi} = (BR_{J/\psi\to\mu\mu})^2\, \sigma_{J/\psi J/\psi}\, L_{int}\, A\, \epsilon$$

ALICE ($2.5 < y < 4$): $A\,\varepsilon \sim 0.05$ (assuming the first pair is triggered by a 1 GeV/c μ trigger threshold with $A\,\varepsilon \sim 0.15$) arXiv:1506.08804

LHCb ($2 < y < 4.5$): $A\,\varepsilon \sim 0.23$ PLB 707 (2012) 52-59

| J/ψ pair yield in Run 2 | p-p@13 TeV | p-Pb@8 TeV | Pb-Pb@5 TeV |
|---|---|---|---|
| ALICE (2.5<y<4) | 50 ($\mathcal{L}$= 40/pb) | <10 ($\mathcal{L}$= 10/nb) | <10,260,500 ($\mathcal{L}$= 1/nb) |
| LHCb (2<y<4.5) | 107k ($\mathcal{L}$= 10/fb) | <10,20,30 ($\mathcal{L}$= 10/nb) | |

p-p: high statistical sample in LHCb, statistically limited in ALICE
p-Pb: possibility to sum-up p-Pb and Pb-p to search for signals
Pb-Pb: feasibility depending on relative SPS and DPS contribution in p-p collisions

prompt J/ψ extraction not feasible yet in ALICE at forward-y: contribution from b-hadrons?

# Inclusive J/ψ pair: beauty contribution

In Run 2 in ALICE/forward-y: no forward tracker before the absorber to select/remove non-prompt J/ψ (planned for Run 3)

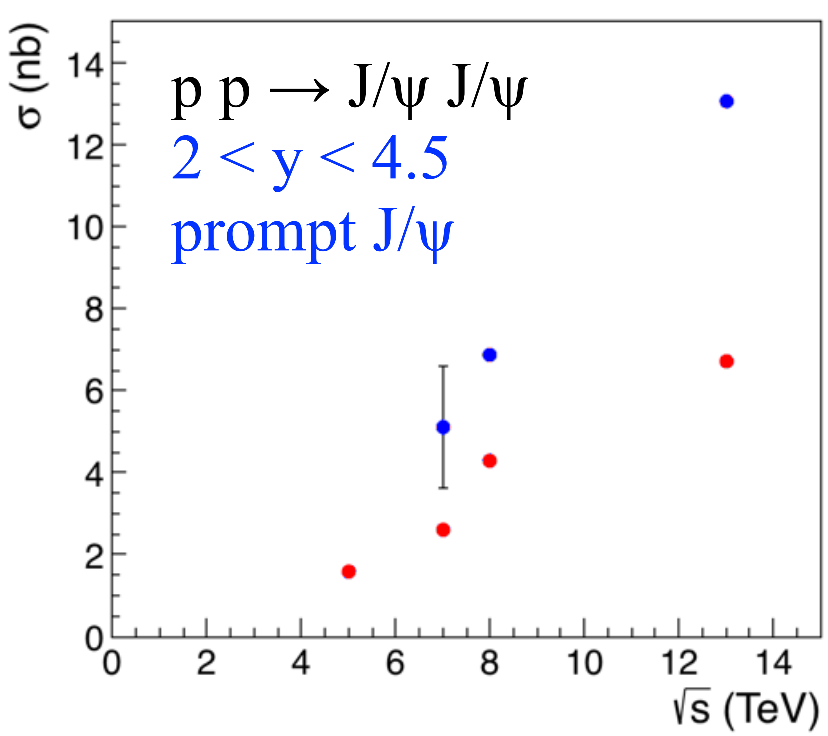
Simple estimation of beauty contribution @13 TeV in LHCb, JHEP1510(2015)172

$\sigma_{4\pi}(pp \rightarrow bb) = 515 \pm 2 \pm 53\ \mu b$

$BR\ (b \rightarrow J/\psi) = (1.16 \pm 0.10)\%$

$\sigma_{4\pi}(pp \rightarrow bb \rightarrow J/\psi\ J/\psi) = (BR_{b \rightarrow J/\psi})^2 \times \sigma_{4\pi}(pp \rightarrow bb) = 70$ nb

bb from $4\pi$ to $2 < y < 4.5$ => 30%: $\sigma\,(pp \rightarrow bb \rightarrow J/\psi\ J/\psi,\ 2 < y_{bb} < 4.5) \sim 14$ nb




(bb → J/ψ J/ψ) same order of magnitude than (prompt J/ψ J/ψ) → it will dilute $R_{AA}$ (J/ψ+J/ψ)

# $J/\psi+\mu$ production at forward-y

Since luminosities are limited in p(Pb)-Pb in Run2, try out $J/\psi+\mu$ as a probe of $J/\psi$+open heavy flavour in ALICE

Only high-$p_T$ $\mu$ ($p_{T,\mu} > 4$ GeV/c) are considered (hadronic background is large at lower $p_{T,\mu}$)

LHCb results on $J/\psi$+open charm support DPS contribution with $\sigma_{eff} \sim 14$ mb

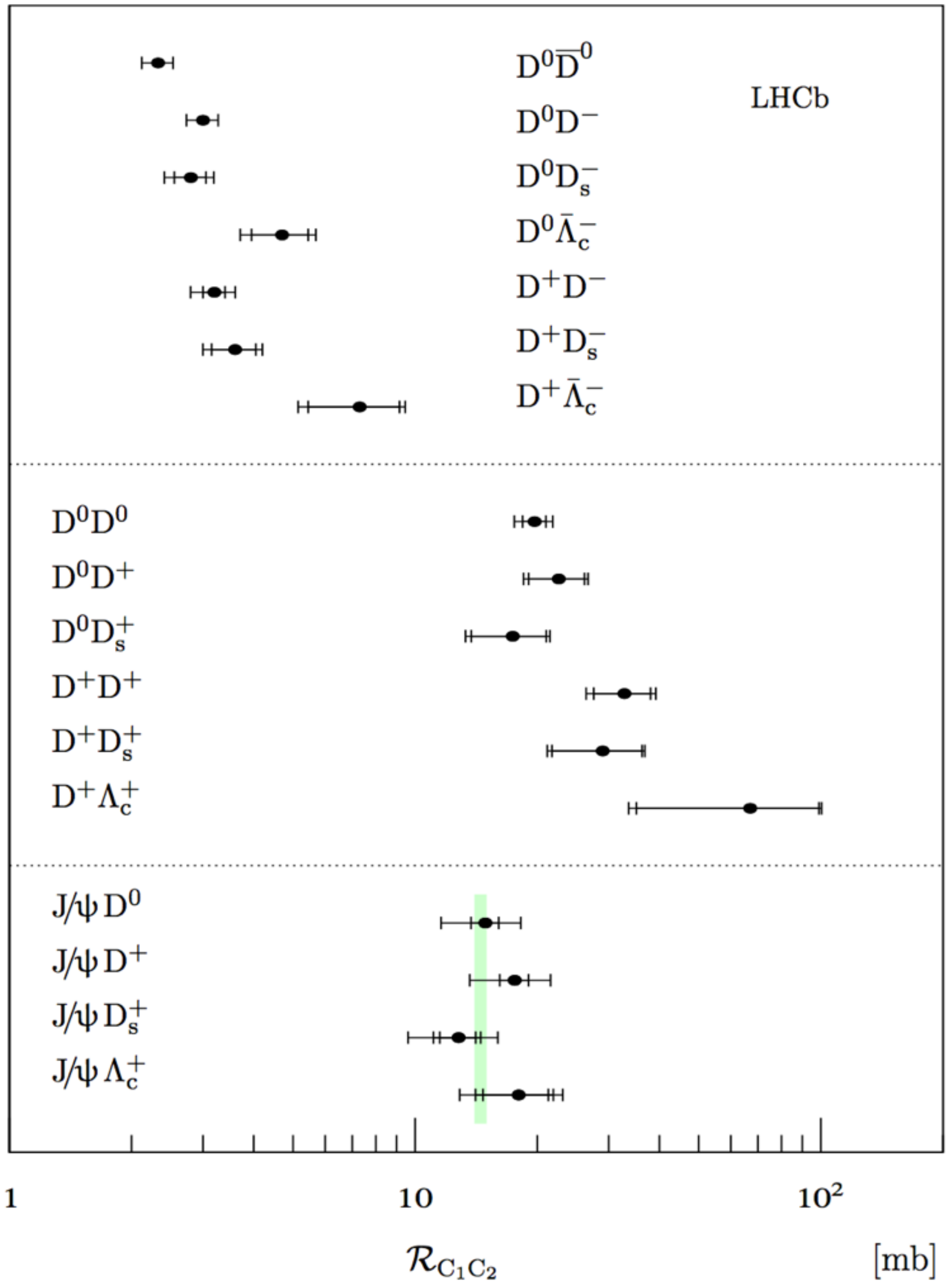
$$\mathcal{F} = 1 \text{ ?}$$

Yields calculated using DPS formula:

$$\left.\frac{d\sigma^{J/\psi+\mu}}{dp_T}\right|_{p_T^\mu=4\ \mathrm{GeV}/c} = \frac{1}{\sigma_{eff}} \times \sigma^{J/\psi} \times \left.\frac{d\sigma^{\mu}}{dp_T}\right|_{p_T^\mu=4\ \mathrm{GeV}/c}$$

with $\sigma_{eff} = 14$ mb

JHEP06 (2012) 141 Addendum



# J/ψ+μ production at forward-y vs √s

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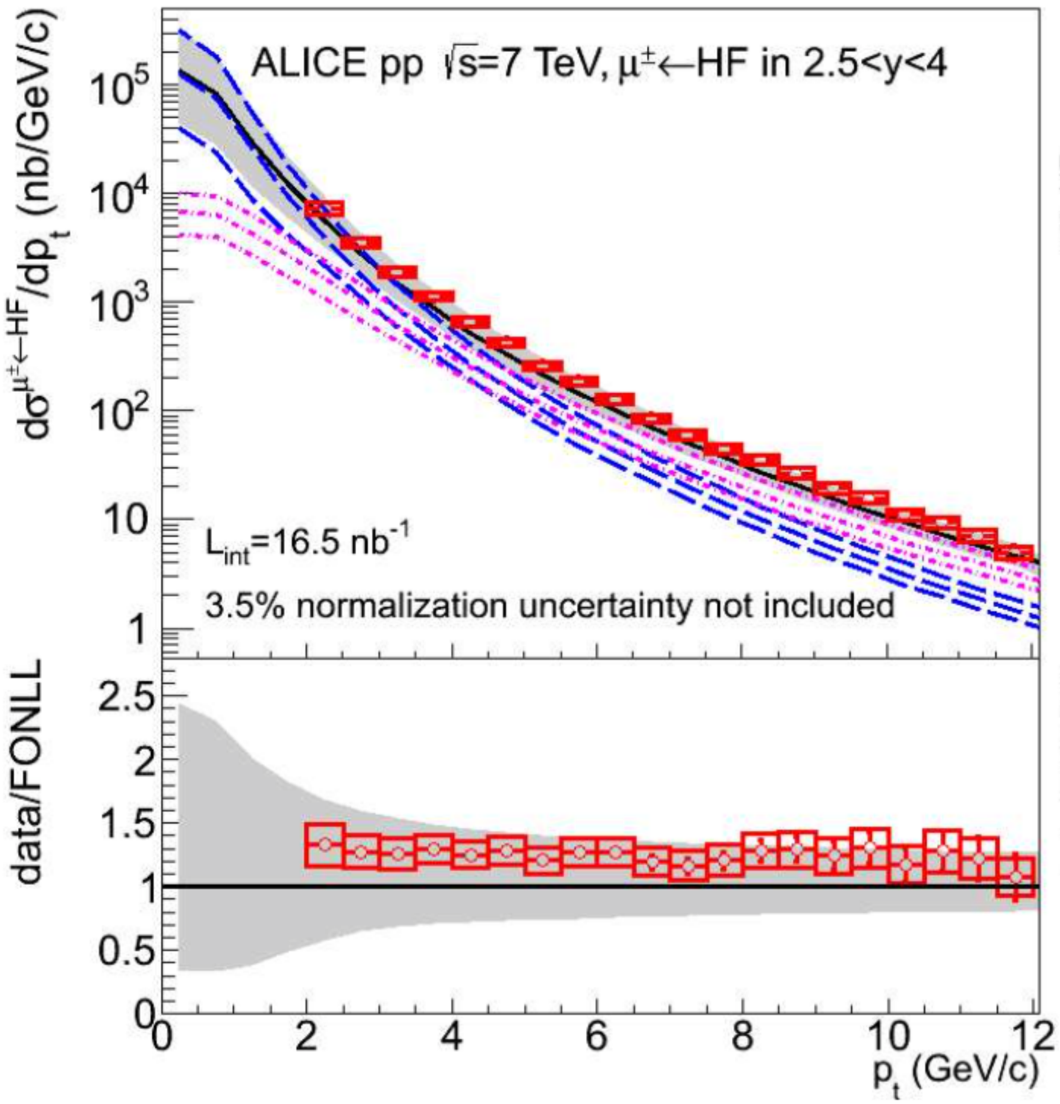
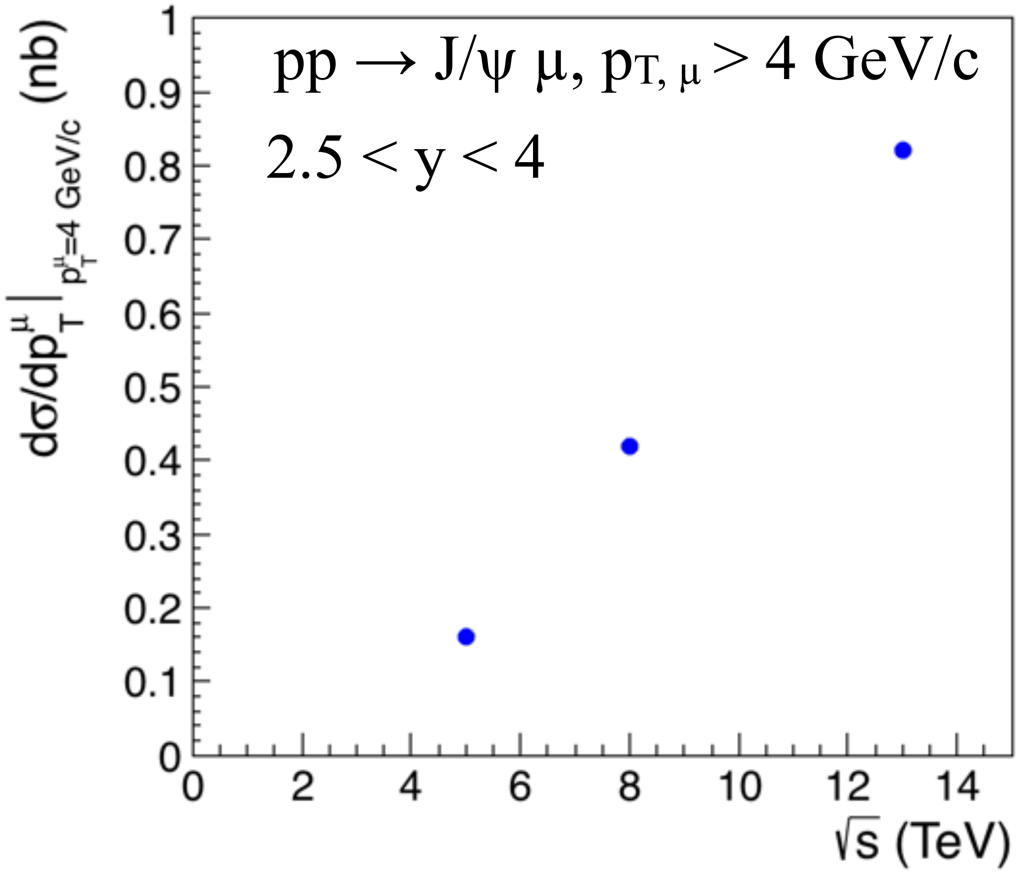
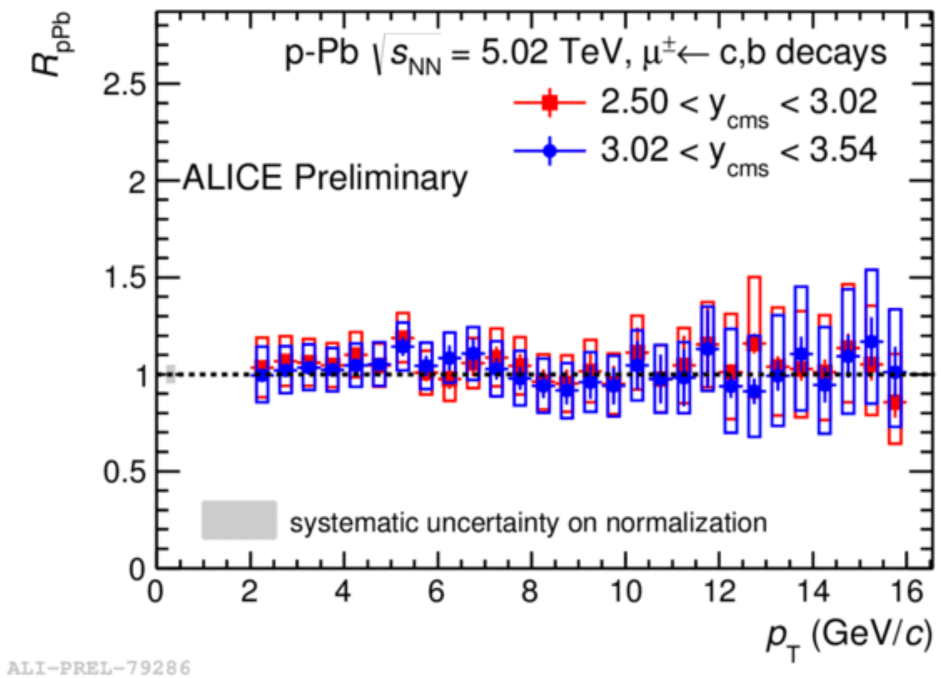



Assumption for √s-dependence: single muon production increases linearly with √s



# J/ψ+μ production: nuclear modification factor



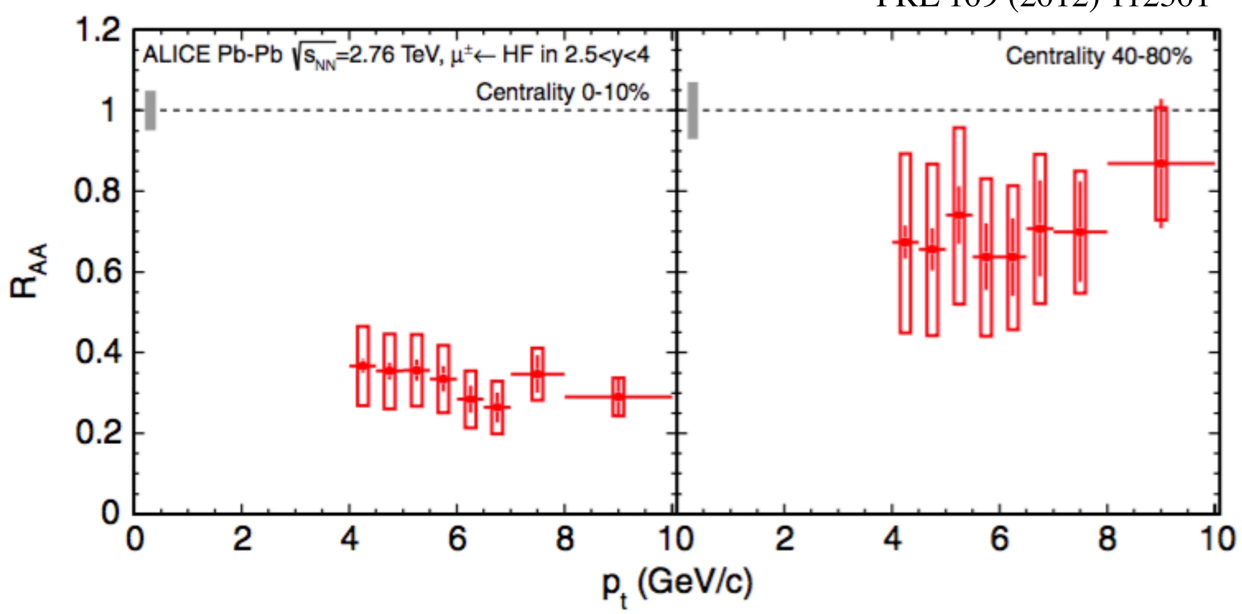

**p-Pb collisions**

$R_{pPb}(\mu) = 1$

$$R_{pA}^{P_1+P_2} = R_{pA}^{P_1} \times R_{pA}^{P_2} \times \left[(1-\mathcal{F}) + \sqrt{\frac{A}{10}}\mathcal{F}\right]$$

$\mathcal{F} = 0, 1/2, 1 \quad \rightarrow R_{pPb}(J/\psi+\mu) = 0.7,\ 1.9,\ 3.2$

PRL 109 (2012) 112301




**Pb-Pb collisions**

$R_{PbPb}(\mu) \sim 0.35$

$$R_{AA}^{P_1+P_2} = R_{AA}^{P_1} \times R_{AA}^{P_2} \times \left[(1-\mathcal{F}) + \frac{A^{1.3}}{5}\mathcal{F}\right]$$

$\mathcal{F} = 0, 1/2, 1 \quad \rightarrow R_{PbPb}(J/\psi+\mu) = 0.2,\ 23,\ 45$

# J/ψ+μ production rates at forward-y in Run 2

$$N_{J/\psi\mu} = BR_{J/\psi\to\mu\mu}\,\sigma_{J/\psi\mu}\,L_{int}\,A\,\epsilon$$

ALICE: $A\,\varepsilon \sim 0.15 \times 0.9 = 0.13$ (assuming the μ pair is triggered by 1 GeV/c μ trigger threshold)

| $dN_{J/\psi+\mu}/dp_T$ ($p_{T,\mu}$ = 4GeV/c) | p-p@13 TeV | p-Pb@8 TeV | Pb-Pb@5 TeV |
|---|---|---|---|
| 2.5 < y < 4 | 270 ($\mathscr{L}$= 40/pb) | <10,15,20 ($\mathscr{L}$= 10/nb) | 10,1400,2700 ($\mathscr{L}$= 1/nb) |

- p-p and p-Pb studies statistically limited in ALICE: decreasing the $p_T$ muon threshold (4→2 GeV/c) leads to an increase of cross-section by a factor 10, resulting however to a larger background contribution
- Pb-Pb: feasible depending on relative SPS and DPS contribution in p-p collisions

Prompt J/ψ extraction not feasible in ALICE at forward-y in Run 2 (upgrade planned for Run 3): contribution from b-hadrons to be estimated

# J/ψ+D production rates at forward-y in p-Pb

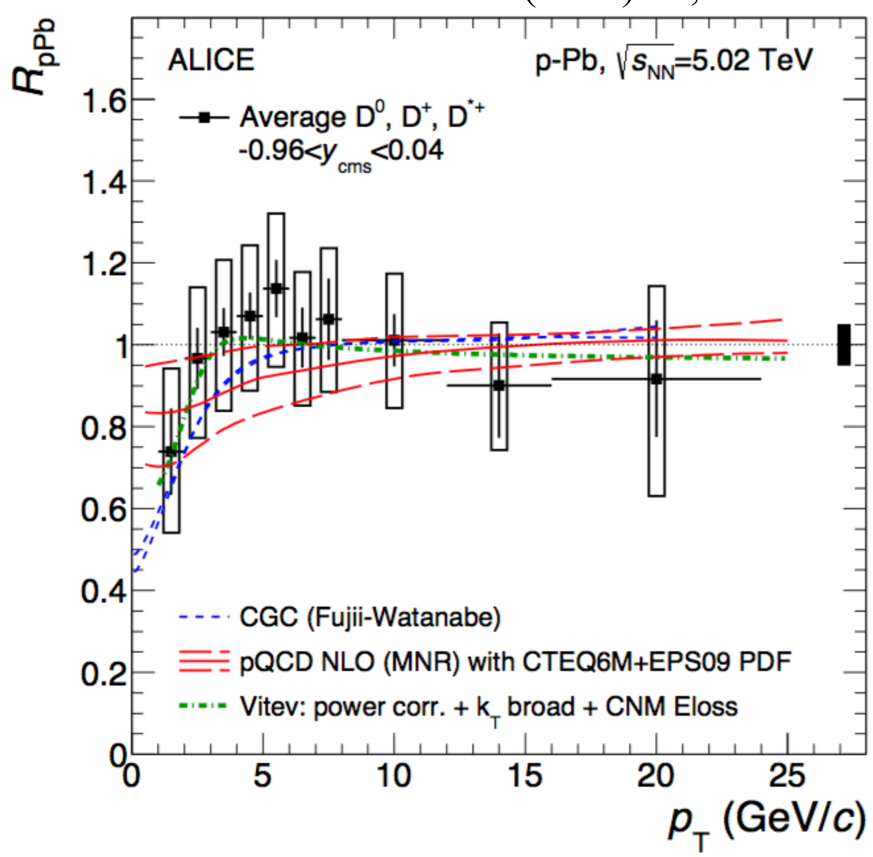
LHCb results JHEP06 (2012) 141

$2 < y_{J/\psi,D} < 4$ and $p_{T,D} > 3$ GeV/c

σ (J/ψ+D) = 161±3.7±12.2 nb @7TeV

with $L_{int}$ = 355/pb and N(J/ψ+D) ~ 5k

PRL113 (2014) 23, 232301




**p-Pb collisions**

$R_{pPb}$ (D) ~ 1

$$R_{pA}^{P_1+P_2} = R_{pA}^{P_1} \times R_{pA}^{P_2} \times \left[(1-\mathcal{F}) + \sqrt{\frac{A}{10}}\mathcal{F}\right]$$

$\mathcal{F} = 0, 1/2, 1$ → $R_{pPb}$ (J/ψ+D) = 0.7, 1.9, 3.2

| $N_{J/\psi+D}$ ($p_{T,D}$ > 3 GeV/c) | p-Pb@8 TeV |
|---|---|
| 2 < y < 4 | 20,54,90 ($\mathscr{L}$= 10/nb) |

→ Same luminosity expected in Pb-p

→ Statistically limited for J/ψ + D but feasible

# Conclusion

- Associated J/ψ production in heavy-ion collisions is expected to be enhanced by nuclear scaling → nuclear modification factor in p-Pb and Pb-Pb can be very high for J/ψ+J/ψ and J/ψ+open heavy flavour depending on the SPS and DPS relative contribution in p-p collisions

- Simple assumptions allow to calculate the expected yields at forward rapidity at LHC in Run 2 for J/ψ pair, J/ψ+μ ($p_T$>4 GeV/c) and J/ψ+D production

- J/ψ pair production can be nicely studied in p-p@13TeV with LHCb and with limited statistics in Pb-Pb@5TeV with ALICE in Run 2

- J/ψ+μ ($p_T$>4 GeV/c) production can be used as a probe of J/ψ+open heavy flavour with reasonable statistics in p-p@13TeV and Pb-Pb@5TeV with ALICE. Beauty contribution needs to be studied precisely

- J/ψ+D promising in p-Pb@8TeV with LHCb

- More opportunities in Run 3 in heavy-ion